Biological Principles to Guide Estimation of Stand Volumes

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ABSTRACT: *Some basic considerations are illustrated with data for several of the commercial tree species of British Columbia. Methods for derivation of stand-volume equations from combined-variable equations for individual trees are described briefly. Relationships among number of trees, basal area, d.b.h., crown width and height which should help extend the applications of stand volume estimates in forest management are suggested. Use of these should result in expressions which are both statistically sound and compatible with the biological relationships governing growth and yield.*

INTRODUCTION

ALTHOUGH much has been learned about the use of aerial photographs for forestry purposes, techniques for estimation of stand volume have not progressed rapidly. A need exists for time to gain experience and to determine what can be seen and measured well on photos. A difficulty has been the numerous approaches tried and incompletely tested by many foresters with relatively limited background in either statistics or photogrammetry. Perhaps most important of all has been the lack of clear biological and economic guidelines to aid in developing improved use of aerial photos.

Since most studies have involved solution of multiple-regression equations, and a synthesis of errors from a variety of sources, it would be helpful to consider a model of how stands should appear before measuring what actually can be seen. Little advantage is to be gained from use of expressions which may be mathematically correct but which are in error biologically. For example, although volume per acre must increase directly with stand height and crown closure, some published equations have stated that volume per acre decreased with increasing crown closure. This relationship could only be correct when the *d.b.h.* (Diameter Breast High) limit of trees sampled is rather large e.g., Allison and Breadon (1960).

The approaches described here apply best to relatively pure even-aged stands, but the principles involved should have much wider application. If a stand is multi-storied, has been disturbed by partial cutting, or is a mixture of hardwoods and softwoods, each component might be treated separately in intensive studies. If species composition can be defined adequately in the initial typing there may be no need for further classification within stands. Usually, classification of species within stands should be by percentage of total volume determined either by photo-interpretation or by ground-checking.

MEASURE STANDS, NOT TREES

The major advantage from use of aerial photos in sampling is the opportunity to reduce error variance by stratification into forest types. Beyond this there is little economic advantage to measuring all individual trees within plots. By use of basal area and height Spurr (1952) found a standard error of estimate of only 5 per cent of the volume per acre of well stocked plots of Douglas fir. Smith and Ker (1959) found a standard error of estimate of 20% of the volume per acre of mixed stands of Douglas fir, hemlock, and cedar when using the combined variable, $H_{max} \times$ *basal area*. Standard errors of estimate, even of the latter size, seem of minor importance when consideration is given to the much larger number of measurements and consequently greater costs required to find volume per acre from individual-tree measurements. Even if all individual trees could be measured precisely on aerial photos it is doubtful that the time involved in measuring and summarizing the data on individual trees within plots would be well spent.

CONSIDER AVERAGE TREE VOLUMES

If stand volume is to be estimated it can come directly from the *d.b.h.* and height of the tree of average basal area, or of average $(d.b.h.)^2$. There is little advantage to deriving empirical tables or equations of volume. The effort usually spent on this should be reserved for controlling and improving the quality of photography and of photo mensuration.

After working in the field of forest photogrammetry for many years, Pope (1962) concluded that the best approach to construction of photo-volume tables is through use of ground-measured height of dominant and codominant trees, H, and photo-measured crown closure, CC. Crown width, CW, has seldom proved to be a useful additional variable with H and CC (Smith, Lee, and Dobie, 1960). In some cases use of H by itself, has been suggested. Then the logical next step is to do away with construction of empirical tables and instead construct stand volume tables directly from combined-variable equations of individual tree volumes.

A General Equation for Stand Volume Tables

It will be shown that stand volume per acre Vpa in cubic feet equals 1.21 times the height in feet of the tree of average basal area times percentage crown closure. This is based on the assumption that the cubic foot volume of the tree of average basal area Vt equals $0.00545D^2$, multiplied by total tree height H, multiplied by a cylinder form factor F, which is often 0.4. Vpa will equal the number of trees per acre NT, multiplied by Vt. NT can be found by assuming that the average tree will have a crown occupying a circle with diameter equal to the average crown width CW, and that percentage crown closure will represent the proportion of the average acre that is covered with trees. Then

$$NT = \frac{43{,}560}{0.7854\,CW^2} \times 0.CC \qquad (1)$$

and $Vpa = NT \times Vt$ which, if CW in feet equals $144D^2$ in inches (i.e. CW/D equals 1), reduces to $1.21\,HCC$. (2)

This very rough formula which assumes that CW in feet equals D in inches can be replaced easily by a new constant based on actual data for H and CC measured on plots whose volume is known. The ratio of crown width to $d.b.h.$ will range from 0.7 in dense to about 2.0 in open stands and, therefore, the volume per acre can range from about $1.21/0.7^2$ to $1.21/2^2$ times HCC. From this example it is evident that measurements of crown width cannot contribute much to estimates of volume per tree unless they are adjusted for stand density. Not only does number of trees per acre decrease directly with increased crown width but also volume per tree of the same height will increase directly with the stand density represented by a given average crown width.

If combined-variable equations for total cubic-foot volume of individual trees, such as those of Smith and Breadon (1964), are available these can be used directly to define stand volume. The height of the tallest 40 trees per acre can be reduced to find the height of the tree of average basal area. Percentage crown closure can be estimated and converted to number of trees per acre by use of average crown width (Equation 1). Then the ratio of crown width to $d.b.h.$ can be chosen following inspection of the ratio of H/CW or study of the crowding within the area actually occupied by tree crowns. The product of volume per tree from $a+bD^2H/100$ and calculated number of trees will give volume per acre.

Of course a simpler approach would be to replace the cylinder form factor of 0.4 used in Equation 2 by a value F' for the species chosen after inspection of the multipliers for H reported by Smith and Breadon (1964). Equation 2 then becomes $1.21\,HCC \times 0.4/F'$. Volume per acre also can be calculated directly by use of estimated basal area and volume to basal area ratios of Smith and Breadon (1964).

Stand density (degree of crowding within area stocked) as well as stocking (crown closure) must be considered since at 100% crown closure the volume for open-grown trees of a given $d.b.h.$ will be only $\frac{1}{6}$ that in a stand averaging the same $d.b.h.$ with normal stand density. This is because, even with 100% occupation of the area with tree crowns, in the open stand there will be only 25% of the normal number of trees and stand height will be only 55% of normal height for that diameter at breast height (Smith, Ker, and Csizmazia, 1961).

Localizing Stand Volume Tables

The B. C. (British Columbia) Forest Service approach based on total cubic foot volumes per tree with appropriate reduction factors for degree of utilization and for waste, breakage, and defect has many advantages. When their standard tables are expressed in combined-variable form (Smith and Breadon, 1964), equations can be derived directly for photocruising. Then the total cubic foot volumes estimated per acre can be reduced for the average degree of utilization expected for the average tree. In addition the percentage of residual or suspect trees can be estimated after consideration of the stand condition and can be used with the average diameter to find deductions for waste, breakage, and decay.

B. C. Forest Service taper curves or stem profiles can be used for average trees to make further breakdowns of the distribution of volumes by size or product classes. They may also be scaled to *f.b.m.* thousand board feet or other units of measure.

If the distribution of trees by *d.b.h.* class is needed, average *d.b.h.* can be plotted on cumulative-frequency, arithmetic-probability paper at 50% and the upper and lower limits set for many stands at 0.5 and 2.0 times average *d.b.h.* which would be plotted at the 1 and 99 per cent levels, respectively. The appropriate percentage of trees for each *d.b.h.* class can then be read from this line to help form a stand table.

Factors Influencing Average Tree Volume

D.b.h. is the most important variable and is followed closely in utility by height. When combined as D^2H small further effects of species are caused primarily by variations in bark thickness and form. Bark thickness is influenced also by age and site. Form, which is influenced by age and site but controlled primarily by stand density, can be estimated roughly by consideration of crown class and length of live crown, or by estimation of CW/D through H/CW which can be measured on aerial photos.

Open-grown trees will have a cylinder form factor of about 0.33 in comparison with 0.4 for forest-grown trees.

A substantial loss in precision results from estimation of cubic foot volume per tree by photo-measurable variables. For example, use of D^2H to estimate volume of 51 Douglas firs accounted for 95.2% of the variation in volume in comparison with 78.7 for HCW. In a group of 62 western red cedars D^2H accounted for 92% of the variation in cubic foot volume in comparison with about 78% for HCW. Ninety hemlocks had 96.8% of their variation in volume accounted for by use of D^2H but only 69% with HCW. Since all these values of H and CW had been measured carefully on felled trees, further substantial errors must result from their replacement by photo-measured H and CW.

Factors Influencing Number of Trees per Acre

Because counting of trees is difficult even on large scale photos it is fortunate that trees per acre can be estimated directly through crown closure and average crown width by Equation 1.

It is essential to distinguish between stocking and stand density. At the extremes one may have 100% of crown closure with trees at any level of stand density from fully open through normal to dense (Smith, Ker, and Csizmazia, 1961). Since the number of trees per acre in a fully open stand, with crowns just touching at square spacing, will only be 25% of the number in a normal stand of the same average *d.b.h.*, stand density obviously must be considered. The ratio of H/CW will be about 5 in normal stands, 2.5 in open, and will seldom exceed 8 in dense stands.

Factors Influencing *d.b.h.*

Smith and Ker (1960) suggested some convenient generalizations for the range of *d.b.h.* about the average for the stand. In natural stands of Douglas fir and hemlock the *d.b.h.* of the smallest trees usually is about 0.5 and the largest about 2 times average *d.b.h.* There is a strong relationship between height and *d.b.h.* but this can be altered radically if trees have been grown from open toward normal stand density. On the same site open-grown trees will have a *d.b.h.* about twice that of normal trees of the same age.

The diameter of the tree of average or maximum height can be estimated from height with due consideration of stand density.

Estimation of *d.b.h.* from Crown Width

For normal stands of many British Columbia species the ratio of crown width to *d.b.h.* is about one. This increases as the stand becomes more open until the ratio of CW/D is about two. In very dense stands the ratio of CW/D is as little as 0.7. If the degree of crowding cannot be recognized from photo-interpretation, the ratio of H/CW can be used in second growth stands to identify the class of stand density and to estimate *d.b.h.* indirectly from crown width.

Because of the great influence of stand density on the regression of crown width on *d.b.h.* it is essential that possible effects at the extremes of stand density be considered in all photo-mensuration studies. Age must also be considered in mature stands and with species like spruce.

Factors Influencing Average Height

In even aged stands best results will be obtained from measurement of as few as possible of the tallest trees per acre. In photomensuration it will be preferable to define height measurements as representing the tallest 40 trees per acre. Then by use of percentage reductions such as those of Smith, Ker, and Heger (1960) the height needed to represent the average tree can be determined.

Factors Influencing Crown Closure

Crown closure is determined quite simply by estimating the portion of the area occupied by tree crowns. It is a very useful variable provided that appropriate consideration is given to the influence of stand density within the area stocked with trees.

Estimating Basal Area per Acre

Smith, Ker, and Csizmazia (1961) have shown that at 100% crown closure, basal area is constant for any average square spacing distance between trees. They also showed that, with regularly distributed trees, crown width and square spacing are equivalent. Therefore, at 100% crown closure, basal area per acre will vary directly with the ratio of $(CW/D)^2$. For example, basal area per acre of a fully stocked stand at the open level of density $(CW/D=2)$ will be 59 square feet. At normal stand density basal area per acre will be 237 and with CW/D of 0.7, as in dense stands, basal area per acre will be 484 square feet.

Basal area per acre will vary directly with percentage crown closure but appropriate adjustments for stand density must be made by consideration of H/CW (open 2.5, normal 5, and dense 8).

Influence of Spacing Pattern

If trees are distributed in a triangular rather than square spacing pattern the number of trees, volume, and basal area per acre can be increased by a factor of $4/\pi$.

Use of H/CW to Estimate Site Index

Spurr (1948, 1960) suggested that in some circumstances site quality might be estimated by use of the ratio of height to crown width, but this ratio appears to be a much better indicator of stand density than of site index. Only 1.7% of the variation in site index of 167 hemlocks was associated with H/CW. About 5% of the variation in site index of 184 Douglas firs was accounted for by H/CW. However, this ratio accounted for 12% of the variation in site index of 77 western red cedars.

Use of H/CW to Estimate Volume

In one analysis of 15 plots, averaging 9,580 cubic feet in volume per acre with a standard deviation of 2,551 cubic feet, H/CW was superior to both H and CW in estimation of volume. The best single variable was crown closure which accounted for 81.5 per cent of the variation in volume. Use of H/CW with CC added only 0.8 per cent.

In another analysis of 15 plots, averaging 8,201 cubic feet per acre with a standard deviation of 2,553 cubic feet, correlation coefficients were determined for volume on the ground-measured variables: number of trees per acre, average diameter, crown class, height, crown width, basal area, and H/CW. Only height $(r=0.58)$ and basal area $(r=0.93)$ were significantly associated with volume per acre.

Data from a total of 84 plots in the University of British Columbia Campus Forest also were analysed. Total cubic foot volume per acre averaged 4,798 with a standard deviation of 2,431 cubic feet. Simple correlation coefficients for volume on ground-measured H, CW, and CC were 0.36, 0.32, and 0.19, respectively. Correlation coefficients for volume on photo-measured H, CW, and CC were 0.37, 0.17, and 0.26, respectively. Some improvement was gained by use of various combinations. CW^2 had a correlation coefficient with volume of 0.31, $H\times CW^2$ 0.36, $H\times CC$ 0.43, $H\times CW\times CC$ 0.46, and H^2CW gave 0.43, but the correlation coefficient for volume on H/CW was only 0.05. All of the combinations tested were based on ground measured variables. Prospects for improvement by combination of old, or introduction of new, independant variables appear poor. The best single estimate of plot volume came from use of a multiple-regression equation based on photo-measured H, CC, and CW which resulted in a multiple correlation coefficient of 0.66.

Conclusion

Although impressive examples can be cited of savings in time and money by estimation of stand volume from aerial photos, most estimates are of low accuracy. Therefore, it seems preferable that time be spent in improving photography and the accuracy of

(*Continued on page 95*)

TABLE 1

ϕ	0°	5°	10°	15°	20°	25°	30°	35°	37°
B/H	0	.28	.56	.88	1.23	1.67	2.24	3.56	3.50
d/H	.77	.72	.69	.66	.64	.62	.61	.61	.60
M_{hm}/S_0	∞	4.18	2.11	1.36	1.00	.77	.62	.50	.47

CONCLUSIONS

The calibration of a radar antennae can be done with good accuracy using half-base convergent photography. For the particular case of a 60-foot diameter antenna it was shown that an accuracy higher than the specified tolerance could be obtained and that complete coverage would be possible with a single stereo-pair. The author suggests that the same method could be applied in the calibration of any type of antenna. Such a method not only has economic and time-reducing advantages for the calibration of the final reflector surface but also would provide an excellent means for detecting structural deformations at any subsequent date.

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measurement of *H*, *CW*, and *CC* rather than on preparation of empirical photo-volume equations or tables. These can be derived as required by any of the methods described here. Use of the relationships summarized in this paper should improve the quality of photo-mensuration and help ensure that estimates of volume from aerial photos will be reasonably consistent with the biological bases of tree and stand growth.

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